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CPT, STRINGS, AND NEUTRAL-MESON OSCILLATIONS

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A mechanism for spontaneous CPT breaking appears in string theory. Possible implications for present-energy particle models are discussed. A realistic string theory might exhibit CPT violation at levels detectable in current or future experiments. Bounds on CPT from neutral-meson oscillations are considered.

Local Lorentz-invariant field theories of point particles are known to exhibit invariance under the combined discrete-symmetry operations of charge conjugation C, parity reversal P, and time reversal T.[1] This CPT theorem has been experimentally tested in many systems,[2] including high-precision interferometric measurements using neutral kaons. Modern searches for CPT violation can be viewed as limiting small effects that might arise from non-particle physics at a level deeper than the standard model, such as string theory.[3]

The extended nature of strings means that the usual derivation of the CPT theorem does not hold in general. This talk provides a short review of a mechanism for spontaneous CPT breaking in string theory and its possible observable consequences. Details can be found in the original literature.[3–8]

It is known that Lorentz symmetry can be spontaneously broken in string theory[4] as a result of interactions that cannot appear in a normal renormalizable gauge theory in four dimensions. This can be accompanied by CPT violation.[3] The controlling interactions are consistent at the string level, where there are infinitely many particle fields due to the extended nature of the string. When scalars condense in the vacuum, the stringy interactions can trigger instabilities in effective potentials for tensor fields. The resulting vacuum values can spontaneously break Lorentz and CPT invariance.

Some explicit evidence exists that these effects occur in the open bosonic string.[5] The action of the string field theory can be calculated in a level-truncation scheme, and the equations of motion can be solved for extrema of the action. As expected, the results include solutions with nonzero expectation values for Lorentz tensors.

Assuming that the Universe is accurately described at a fundamental level by a realistic string theory, then it is possible that CPT-breaking contributions

could appear in the low-energy (compactified) limit. Generic terms can be obtained that would arise in a low-energy four-dimensional effective theory, which presumably would involve the standard model. For example, a contribution to the low-energy lagrangian could have the form: [5,6]

$$\mathcal{L} \supset \frac{\lambda}{M^k} \langle T \rangle \cdot \overline{\psi} \Gamma (i\partial)^k \psi + \text{h.c.} \quad . \tag{1}$$

For neutral-meson oscillations, ψ can be regarded as a quark field in a meson, coupled through a gamma-matrix structure Γ and possible derivative factors to a nonzero vacuum value $\langle T \rangle$ of a Lorentz tensor T. The quantity λ is a dimensionless constant, while M is a large mass scale such as the Planck mass.

The absence of large CPT violation in nature means that any effects of this type must be suppressed. A natural dimensionless ratio in the theory is $r = m_l/M$, where m_l is a low-energy scale. Suppression by this small quantity could generate effects in neutral-meson systems that are comparable in size to or smaller than current and near-future experimental sensitivities.[3,6]

This possibility can be studied in more detail using an effective hamiltonian Λ controlling the time development of the neutral-meson states. In the standard approach, CPT violation appears in Λ through a phenomenological complex parameter δ_P, with the subscript P representing one of the four neutral mesons K, D, B_d, and B_s. In the context of the string scenario, the expression (1) provides a means of relating δ_P to more basic quantities. It follows that[5,6]

$$\delta_P = i \frac{h_{q_1} - h_{q_2}}{\sqrt{\Delta m^2 + \Delta\gamma^2/4}} e^{i\hat{\phi}} \quad , \tag{2}$$

where Δm and $\Delta\gamma$ are the experimentally observable mass and rate differences for the P mesons, with $\hat{\phi} = \tan^{-1}(2\Delta m/\Delta\gamma)$, and where $h_{q_j} = r_{q_j} \lambda_{q_j} \langle T \rangle$, $j = 1, 2$, are coefficients for the two valence quarks of P that depend on quantities in (1) and on parameters r_{q_j} arising from the quark-gluon sea. Equation (2) can be used to derive relationships between the real and imaginary parts of the parameters δ_P:

$$\operatorname{Im} \delta_P = \pm \cot \hat{\phi} \, \operatorname{Re} \delta_P \quad . \tag{3}$$

These predictions of the string scenario for the P mesons are consequences of the hermiticity of the fundamental string action.

One important feature that emerges from the above results is that the size of any CPT violation arising in this context is potentially very different in different meson systems. The presence of constant dimensionless couplings in Eq. (1) is reminiscent of the standard-model Yukawa couplings, which are known to vary over many orders of magnitude. It is therefore of interest to test for CPT breaking in all neutral-meson systems,[5] not only the K case.

Each neutral-meson system can be examined to determine the limits on CPT violation that could be placed by present and near-future experiments using either correlated or uncorrelated mesons.[6−8] Here is a short summary of a few results emerging from these analyses.

• Currently, only the K-system CPT-violating parameter δ_K has been bounded experimentally. The advent of high-statistics kaon and ϕ factories suggests that improved limits, perhaps even to one part in 10^5, are likely soon.

• Since mixing in the D system is known to be no larger than about 5% and may be much smaller, bounding CPT violation there is difficult. At a τ-charm factory, however, several significant experiments could be envisaged, including ones limiting some kinds of K-system CPT violation as well as direct and indirect CPT violation in the D system.[7]

• Especially interesting limits are feasible for the neutral-B_d system, for which the heavy b quark is involved and CPT violation could be enhanced. Indeed, it is still possible that indirect CPT violation exceeds the more conventional indirect T violation in this system. No CPT limit has yet been published, but recent Monte-Carlo simulations with realistic data incorporating experimental backgrounds and acceptances suggest that sufficient data have already been taken to place a bound on δ_B around the 10% level.[8] Machines currently being developed would have the capability for further improvements.

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2. See, e.g., Review of Particle Properties, Phys. Rev. D **54**, 1 (1996).
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